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## CAA : Jet Noise

- I. Background
  - II. Prediction of the time-dependent sound source using Large-Eddy Simulations (LES)
  - III. Sound propagation to the far-field
- What is Computational Aero-Acoustics (CAA) ?
- CAA is concerned with calculations of the aerodynamically-generated sound source and its propagation:
- The time-dependent flow fluctuations (sound source) are obtained starting from the time-dependent differential equations.
  - High-order accurate schemes and appropriate boundary conditions for wave-like solutions are needed.
  - Differential or integral techniques for sound propagation.

## Noise Produced by Large-Scale Coherent Structure in Subsonic Jets

- The initial region of jet is dominated by large-scale, wave-like coherent structure, which is believed to be the dominant sound source.

- The coherent structure can be calculated by:  
Splitting the flow field into three components: time-averaged, coherent, and random. The coherent component is represented by few frequency modes which are taken to resemble a nonlinear instability wave interacting with the mean flow, turbulence, and other coherent components. Integral equations are then obtained for each scale of motion.

Lighthill theory is used with the stress term given by the coherent structure.

- Acoustic Analogy - Lighthill's Theory:

The coherent component is represented by few frequency modes which are taken to resemble a nonlinear instability wave interacting with the mean flow, turbulence, and other coherent components.

Integral equations are then obtained for each scale of motion.

$$P_s = \frac{1}{4\pi R_\infty a_\infty^2} \iint \iint \frac{\partial^2}{\partial x \partial x_j} (\rho u_i u_j) dV \quad (1)$$

The curly brackets denote that the source term is calculated at the retarded time

$$t_r = t - |\vec{X} - \vec{Y}|/a_\infty \quad (2)$$

where X and Y are the observer's and the source's locations, respectively.

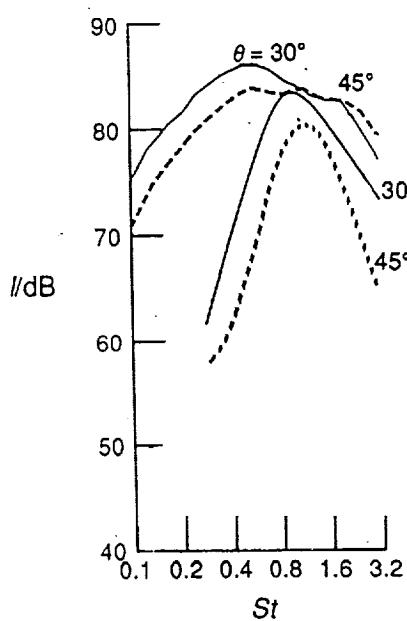
- Working with time-averaged properties

- Modelled time-dependent sound source

- Noise radiation from linear instability wave

- Noise radiation from large-scale coherent structure

Calculated Spectra of Sound Intensity in Decibels Referred to  
 $10^{-12} \text{ W m}^{-2}$  Due to Coherent Structures  
at Various Emission Angles for  $U_e = 195 \text{ m s}^{-1}$



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FIGURE 14. Large-scale structure rms pressure ratio  $(\bar{P}_s)/(\bar{P}_e)$  along the jet centreline: comparison with Moore's (1977) experimental data. (a)  $St = 0.13$ , (b)  $St = 0.24$ , (c)  $St = 0.39$ , (d)  $St = 0.35$ , (e)  $St = 0.50$ .

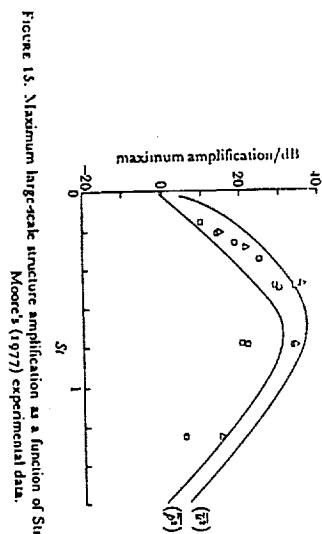
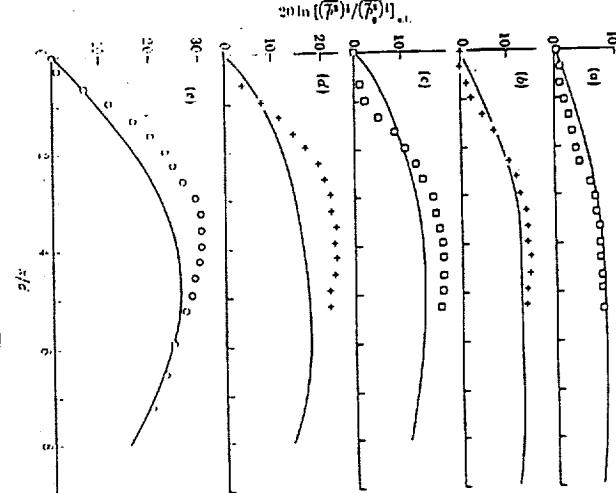


FIGURE 15. Maximum large-scale structure amplification as a function of Strouhal number; comparison with Moore's (1977) experimental data.

## II. Large-Eddy Simulations For Prediction of The Sound Source in a Supersonic Jet

### The Study Indicates:

- DNS can predict the full spectrum of the sound source...But, the resolution requirements are prohibitive.
- In large-eddy simulations (LES) the unresolved, small scales are modelled. The acoustically active, larger scales are obtained directly from simulation.

### The Study Indicates:

- The large-scale structure seems to be the dominant sound source.
- Results are sensitive to approximation in the sound source.
- Lighthill's theory predicts some results consistent with observations and some are not.
  - No explicit Acoustic-Flow interactions
  - Definition of the source term is debatable

## Harmonic excitation

Inflow disturbances in the form

$$\tilde{u} = \bar{u} + e^{-\alpha(t-1)^2} \sum_{j=1}^{16} \sin k_j \omega_j t \quad (5)$$

where  $\omega_j$  was taken  $\pi/8$ . The Gaussian profile of the disturbance was introduced to reduce the adjustment zone.

- Discretization:
- A fourth order accurate in space and second-order accurate in time MacCormick Scheme is used (2-4, Gottlieb & Turkel).

- An operator splitting is used to maintain the 2-4 accuracy, namely

$$Q^{n+2} = L_x L_t L_x Q^n, \quad (3)$$

where  $L_x$  and  $L_t$  are one-dimensional solution operators corresponding to the scheme applied to the equations

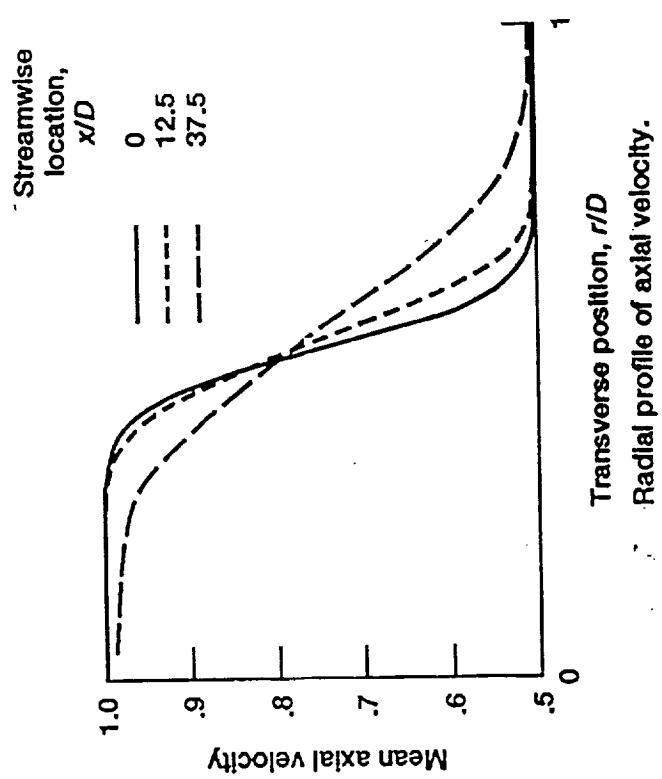
$$Q_t = F_x, \quad Q_x = G_t + S, \quad (4)$$

SGS Model:

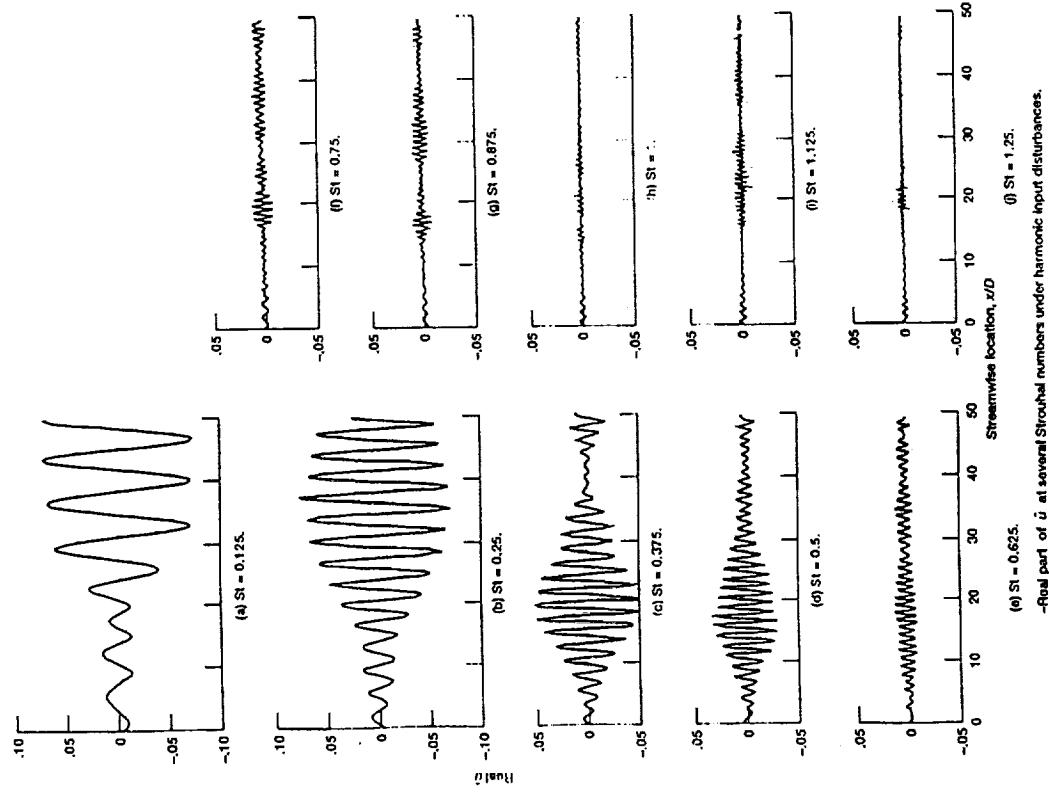
- Smagorinsky's model is used for the SGS turbulence.

Boundary conditions:

- Objective is to obtain the time-dependent ("wave-like") structure. Boundary conditions could create artificial disturbances or could dampen the physical disturbances... Special attention is needed.
- Several outflow boundary conditions are evaluated.
- Linearized characteristics (e.g. Bayless & Turkel) are used to derive the B.C. used herein.



Transverse position,  $r/D$   
Radial profile of axial velocity.



-Real part of  $\hat{u}$  at several Strouhal numbers under harmonic input disturbances.

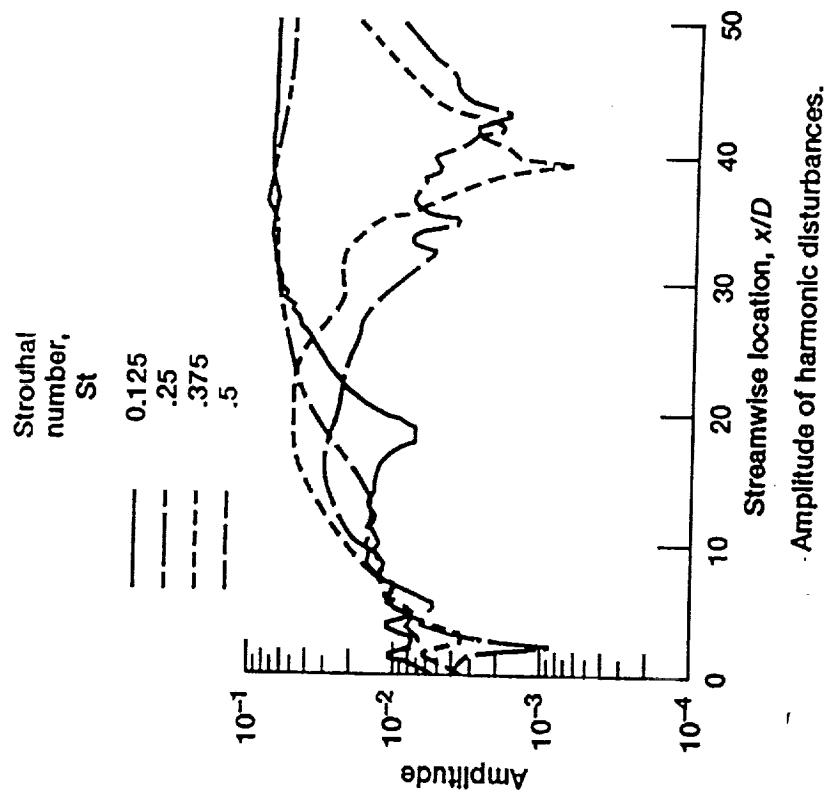
### III. Far-Field Sound

- (1) Extend Navier-Stokes computational domain to the far field:  
(a) Prohibitive storage requirements  
(b) acoustic scales are different from fluid scales.

(2) Lighthill's acoustic analogy

(3) Finite-difference of linearized equations

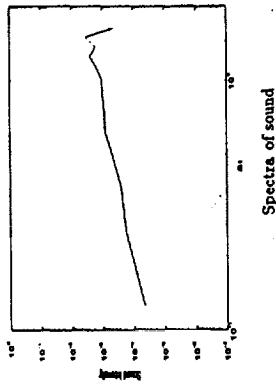
(4) Kirchhoff's method



## (2) Prediction of the Far-Field Sound Using Lighthill's Theory

### (3) Finite-difference approach ... Linearized Euler equations

- Finite-differencing can be used to solve the linearized Euler equations or other equations (Liley, Phillips) describing the sound propagation to the far-field.
- The problem is that numerical dissipation and dispersion can lead to erroneous results for or the far-field sound.
- Goodrich (1993) developed a new algorithm that seems to be useful for this purpose.  
The scheme is tested for 1D linearized Euler equations and seems to be accurate at very long times with few mesh points



## SUMMARY

### FLOW FIELD:

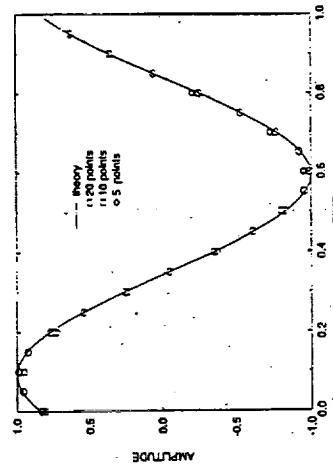
- The time-dependent sound source can be predicted via careful large-eddy simulations.
- For random inflow-disturbances the wave-like nature of the unsteady structure is evident for Strouhal numbers of up to about 1.2.
- The large-scale structure ( $St < 1.2$ ) could be enhanced via harmonic excitation -- Potential for control.
- The higher frequency modes peak closer to the jet exit and the lower frequency ones peak farther downstream.

### FAR-FIELD SOUND:

- Lighthill's: Limited success
  - No explicit account for sound-flow interaction
  - Source is assumed to be compact, but it is no-compact for supersonic jets.
- Finite-Difference:
  - A high-accuracy scheme is being evaluated.
- Kirchhoff's method:
  - The predicted pressure on a cylindrical surface enclosing the jet is used to predict the far-field sound - Most promising.

### (4) Kirchhoff's method

- Outside the source region the sound transmission is governed by the convective wave equation.
- The sound pressure field is given in terms of a surface integral involving the numerically calculated surface pressure.
- Evaluated for a point source.



- Predicted directivity of jet noise seems to be consistent with observation.